Smart DC Grid integration in railway systems

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RESUME – Cet article présente une nouvelle solution écologique pour récupérer l'énergie de freinage des trains par l'intégration d'un Smart DC micro-grid dans les systèmes ferroviaires. Le principe est de stocker l'excès de l'énergie de freinage dans un système de stockage hybride afin de le réutiliser pour alimenter d'autres applications non-ferroviaires qui pourraient être installées dans la station où à proximité, ce qui va améliorer l'efficacité énergétique globale du système.

ABSTRACT – This paper introduces a new green solution to recover trains braking energy by integrating Smart DC micro-grid concept in railway systems. It is based on storing the excess of braking energy in a hybrid storage system and re-using it in non-railway applications such as auxiliary loads in a station or in proximity, which will increase the total energy efficiency.

KEYWORDS – Railway, Smart Grid, Electrical braking energy, hybrid storage system, energy management system

1. Introduction

In December 2008, the European Union (EU) declared its climate and energy targets for 2020, known as the 20-20-20 plan. It defines three key objectives: 20% reduction of EU greenhouse gas emissions from 1990 levels, 20% increase of EU renewable energy consumption and 20% improvement in EU's energy efficiency [1]. According to IEA's 2009 report [2], the transport sector's share of CO2 emissions rises to 23%. It is mostly concentrated in urban areas where the population density is relatively high. Therefore, in railway systems, electric traction implementation is nowadays more beneficial than Diesel traction given the fact that it is more efficient. It represents less energy conversion losses, no gas emission and the capability to regenerate braking energy and to exchange it between trains. But since electrical railway system has a very dynamic power consumption profile, it was considered as particular consumer electrically isolated from other non-railway consumers. Due to the limited capability of the electric delivery system that was designed to provide unidirectional power flow, there was no energy exchange with surrounding consumers and no possibility to integrate distributed energy resources and smart energy management systems. Besides, with the emergence of smart grid concept, it became imminent to introduce innovations in railway sector. It is unlikely to stay away from the technological development observed worldwide in different fields such as communication, information, electronics… Smart railway electrification will provide energy savings by accommodating all distributed generations (braking trains, renewable powers...) and storage options (batteries, supercapacitors, flywheel…). It will dynamically optimize the total power consumption and enhance power quality and system's efficiency. Railway system will no longer be a passive load consuming energy from the grid. It will take part of a larger smart grid and communicate with "non-railway" applications such as smart buildings, electrical vehicles charging station… In addition, operators encounter daily service disruption due to various failures, especially electrical equipment breakdowns. This can be avoided by integrating Smart Grid technology with its self-healing property. It can anticipate system failures by performing continuous self-assessments to detect possible disturbances and take corrective actions. Its intelligence remains in handling problems too large and too fast for human intervention. To achieve its goals, the smart grid's structure is based on the following components:

- Smart sensing and metering technologies: nowadays, the information transmitted to the control room is basically related to signaling and train operation. No real-time data is collected in order to optimize global system's energy signature. It is now possible to receive the dynamic state of the energy system due to communicating measurement tools, some could be integrated in the trains (speed, real position, regenerated power…) and other could be distributed along the infrastructure (voltage and current measurement...).
- Two-way standardized communication infrastructure: a fast and reliable connection should be established between different railway components including trains, metering equipment, electronics… the control center should be able to reach each point of the system.

- Robust software able to control critical situations quickly and efficiently. It should also be configured to operate in a self-healing manner. It will then perform system's diagnosis and take suitable decisions autonomously.
- Flexible and controllable infrastructure: a smart grid is before everything else a flexible grid. Therefore, it is important to ensure that the system is able to command operations from distance. Instantaneous modification of the electrical equipment's status is thus possible. The railway infrastructure and especially converters should also be bidirectional allowing power flow management.

2. Smart DC station

Nowadays, one of the challenges in railway systems is recovering all the braking energy and avoiding losses. In fact, when an electric train brakes, it converts the mechanical kinetic energy to electrical energy and feeds it back to the source line (catenary or 3rd rail). This causes voltage increase at the pantograph. If another train is accelerating closely enough, the energy sent back to the catenary will be normally consumed by this train. In the opposite case, regenerated energy causes overvoltage which can damage the infrastructure. Therefore, when the voltage exceeds the threshold (900V for 750V electrification), the energy is burned in rheostats built in the trains. These energy losses consist 15% of the total traction energy consumption [3]. Instead of losing this energy, many solutions are suggested in order to solve this problem. But given the fact that in DC mode the classic substations consist of classic diode rectifiers, it is impossible to feed energy back to the upper grid because of the unidirectional energy flow. Therefore, one of the possible solutions is the reversible substation that contains a bi-directional inverter [4]. It respects the energy exchange between trains and captures only the excess of energy that would have been burned in rheostats. This solution is affordable in the cases where the electricity supplier accepts to buy the recovered energy at an interesting price especially when it consists of instantaneous and random power peaks. In addition, this solution is not coherent with the energy management concept because it sends back automatically the recuperated energy into the grid without taking into consideration the grid's demand and balance, as for example, regenerating in high-tariff periods and storing energy in low-tariff periods.Therefore, instead of only considering injecting the braking energy in the upstream network, an alternative solution, the smart DC micro-grid, allows to re-use it internally by the same operator but in different electrical applications, for example, lighting and escalators inside a metro station, electrical vehicles and buses parked outside the station... This eco-friendly solution will permit reducing energy losses, saving energy and thereby decreasing the total energy bill. In addition, both solutions, the reversible substation and the DC micro-grid, could coexist if operated by an intelligent energy management system.

In this paper, we will consider a scenario where the braking energy is used to charge electrical hybrid buses parked outside a metro station, thus enhancing the green multi-modal public transport deployment.

2.1 Concept

A pre-fabricated charging station for electric hybrid buses is a critical load consuming high powers in a short period of time (few minutes). It requires a particular subscription contract in order to be connected to the grid and the cost will probably be expensive. Therefore, given the fact that buses stops usually coincide with metro stations, the braking energy wasted in the metros rheostat can be used to charge these buses. However, the braking energy is an unpredictable and discontinuous source of power with large instantaneous peaks (figure 1) which make difficult to use directly without local storage cells to overcome the intermittency of the braking energy and time mismatch between the source (braking energy) and demand (electric buses). Additional energy can be sold back to the grid depending on the status and capacity of the energy storage unit.

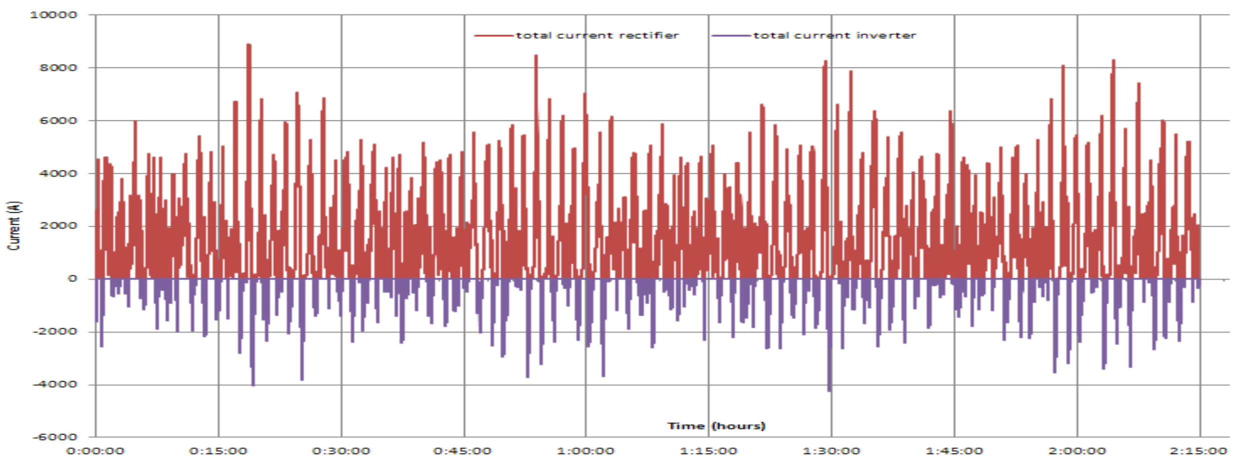

Figure 1: Traction current (red) and braking current (BLUE) at a reversible traction substation extracted from ELBAS

Trains, buses and energy storage devices can be connected using a Smart DC micro-Grid that will manage the energy distribution. It is a DC based concept where the main focus is set on achieving better power quality by aggregating sources and loads through a DC busbar. The DC micro-grid is then connected to the grid through a common DC/AC converter.

Because both loads and sources can interface to a common DC bus bar with fewer redundant stages of power conversion, the result is less wasted heat and potentially lower cost than a pre-fabricated charging station. In addition, a "smart energy management system" will accommodate both intermittent generations as well as loads and optimize power flow between different terminals. It will enable the savings of the 15% metro line wasted energy, and make the recovered energy available for charging the electric hybrid buses parked at a metro station.

As the energy is mainly managed locally, no power quality issues shall arise on the AC grid side even in the case of transformerless operation (as assumed here) and the use of 2-level inverter. This is in spite of the highly intermittent nature of the metro braking energy and the electric bus charging. Moreover, no additional contract with the electricity provider needs to be signed for the bus charging station because it uses a LV AC/DC converter where only a small amount of power is required to regulate the DC bus bar voltage. For example, it could be connected directly to the LV power supply already existing in the metro station.

An example of Smart Micro DC-grid is shown in the figure below:

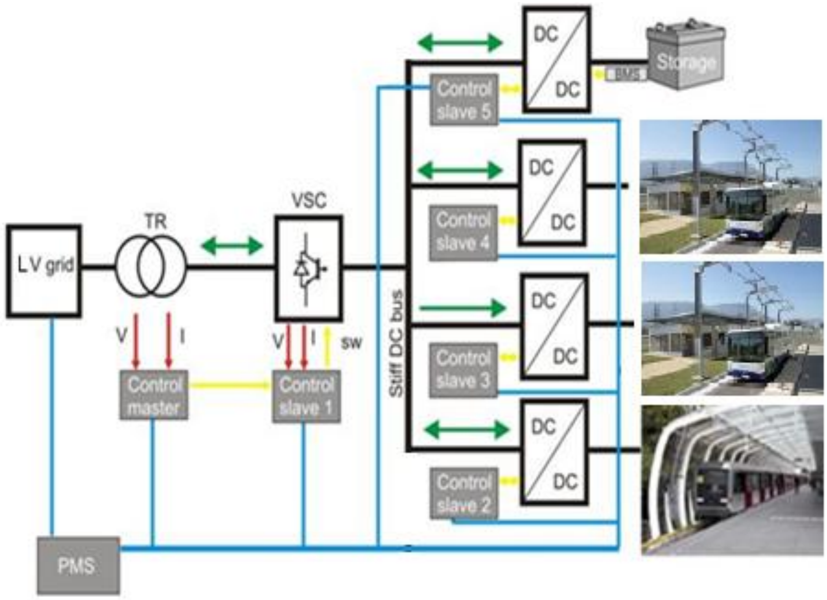

Figure 2: Smart micro DC grid architecture. Black lines: Power transmission; Blue lines: communication signal transmission, red and yellow lines: control signals transmission through electrical connections and fiber optics

2.2 Power electronics architecture

A first study will focus on the solution's architecture. The figure below represents the global architecture of the system:

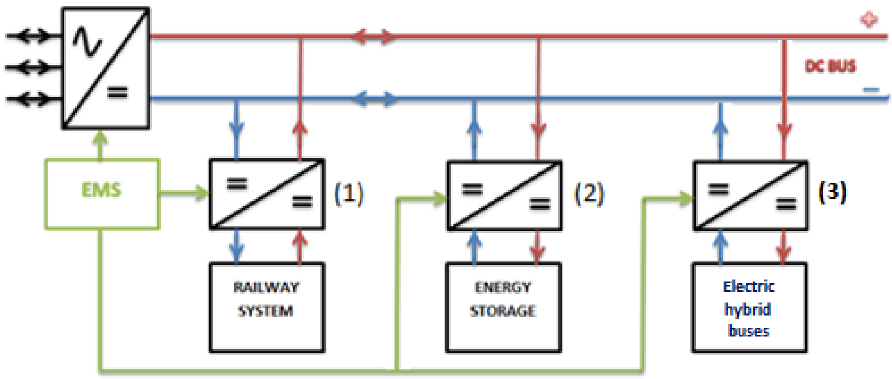

Figure 3 : DC Micro-Grid concept

The DC micro grid architecture consists of the following components:

- A 900V DC Busbar

- 2-level bidirectional inverter connected to the LV power supply already available in the metro station
- DC/DC converters connecting the energy storage (2), railway system (1) and the hybrid buses (3) to the common DC Busbar
- Hybrid energy storage device containing supercapacitors and batteries.

All these components are modelled and simulated using Matlab-Simulink.

When a train brakes, the catenary (or third rail) voltage increases. Once the voltage exceeds a specific threshold and there's no energy exchange between trains, the converter (1) will recuperate the braking energy and inject it into the DC bus. This converter is regulated in a way that respects the energy exchange between trains. Once detecting an accelerating train close enough, the converter will automatically stop recuperating energy. This concept will be detailed in coming publications. Meanwhile, the second DC/DC converter (2) will store the energy and help reducing the DC bus voltage. The AC/DC bidirectional inverter is used to regulate the DC bus voltage to avoid voltage peaks or drops. The Energy Management System (EMS) will optimize energy flow by selecting the proper operation mode, controlling the converters and the storage system's state of charge (SOC).

The system operates in four different modes: Recuperation Mode (RM), Feeding Mode (FM), Standby Mode (SM) and emergency mode (EM). The table below shows the mode selected by the EMS for different possible scenarios. The functions are tagged with the letter "P" followed by a number that indicates the decreasing priority order (Top priority = 1).

Operation Mode	**Railway**	**Supercapacitors**	**Battery**	**Hybrid buses**	**Static Loads**	**Inverter**
RM 1	Braking energy available	SOC < 1 (Charging) P1	SOC ≤ 1 (Charging) P2	Not connected	Connected (consuming) P3	Feeding power to the grid P4
RM 2	Braking energy available	SOC = 1 (fully charged)	SOC = 1 (fully charged)	Not connected	Connected (consuming) P1	Feeding power to the grid P2
RM 3	Braking energy available	SOC = 1 (fully charged)	SOC = 1 (fully charged)	Not connected	Not connected	Feeding power to the grid P1
RM 4	Braking energy available	SOC < 1 (charging) P2	SOC ≤ 1 (charging) P3	Connected (Charging) P1	Connected (consuming) P4	Feeding power to the grid P5
SM	No braking energy	Standby	Standby	Not connected	Not connected	Standby
FM	No braking energy	SOC>25% (discharging) P1	SOC>30% (discharging) P2	Connected (charging) P1	To be disconnected	Consuming power from the grid P3
EM	Fault detection (a need to feed power into the catenary or 3rd rail)	SOC>25% (discharging) P1	SOC>30% (discharging) P2	To be disconnected	To be disconnected	Consuming power from the grid P3

Table 1 : EMS operation mode selection

2.2.1 AC/DC bidirectional inverter

The inverter is used to regulate the DC busbar voltage. It feeds back energy to the grid when the voltage is higher than 940V and consumes energy from the grid when the voltage is lower than 860V. This 80V dead zone gives the priority to the storage system (figure 4).

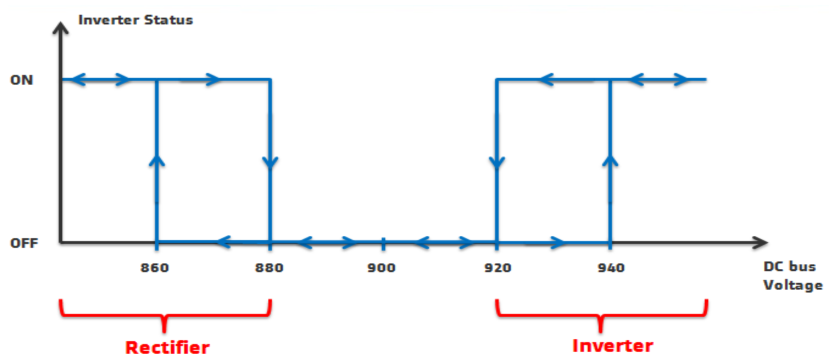

Figure 4 : Bidirectional inverter ON/OFF command

The inverter's regulation consists of two cascaded control loops. The first one regulates the DC Busbar voltage. It generates the reference current on the AC side. The second loop regulates the AC currents to match the reference current. It generates the inverter's three phase reference voltages that are converted into 6 pulses, using PWM, that command the inverter's IGBTs.

When the inverter recuperates the energy, the DC Busbar voltage is regulated to 920V. Contrarily, when it injects energy from the grid (rectifier role), the DC Busbar voltage is then regulated to 880V.

In addition to the voltage regulation, the inverter operates with a unitary power factor at the AC side in both generation and consumption modes. The figure below shows the control blocs simulated in Matlab-Simulink:

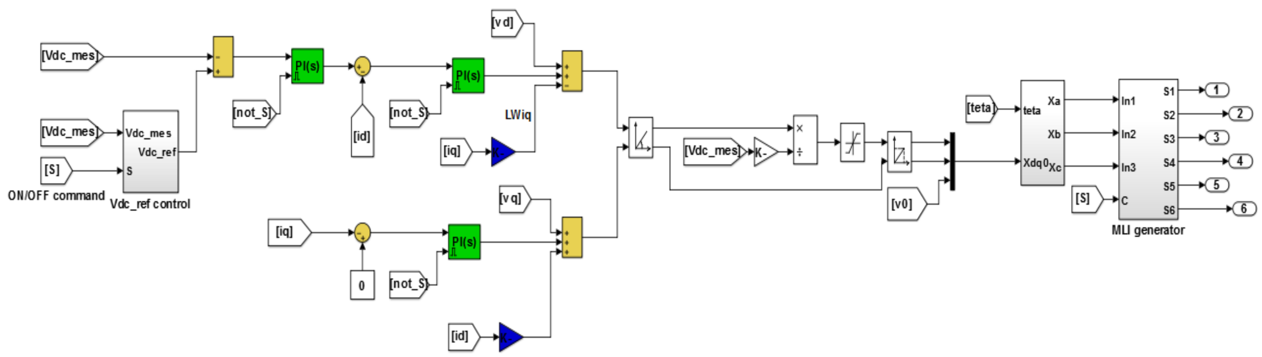

Figure 5 : Inverter control loop

The figure below shows the current and the voltage measured at grid's side:

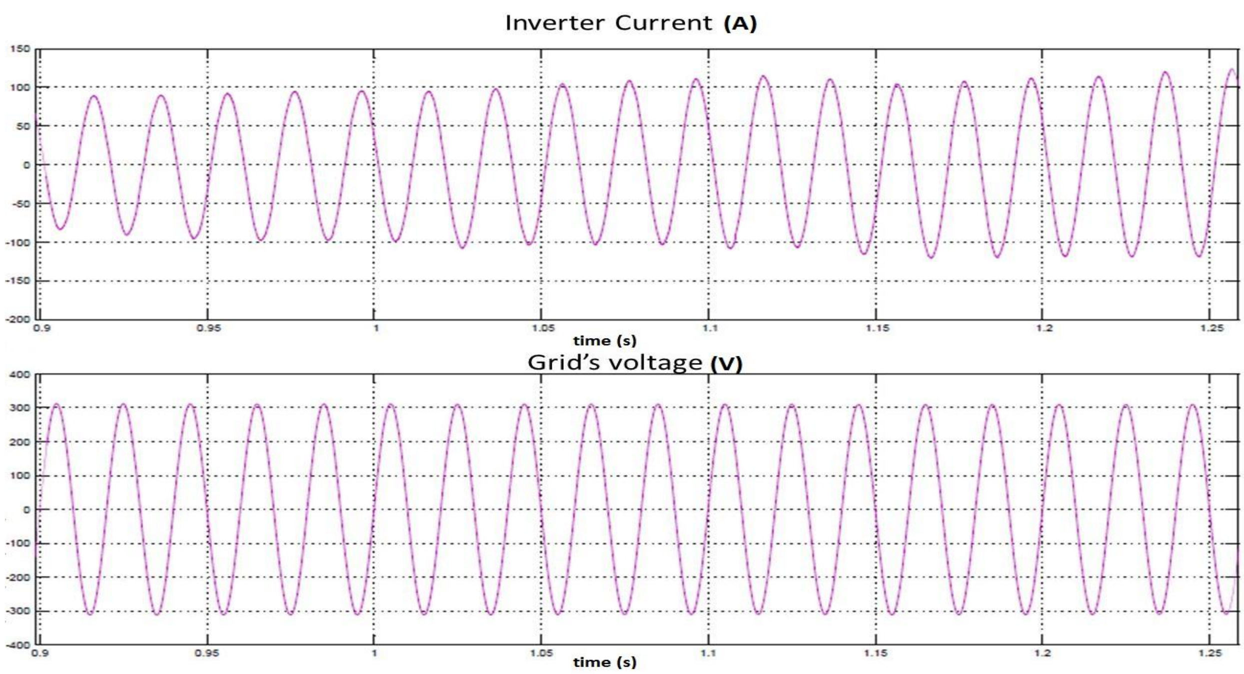

Figure 6 : Current and voltage at grid's side

2.2.2 Hybrid energy storage system

In order to adapt an unpredictable source of power to a short time constant charge, energy storage systems need to be integrated. Currently, the most commonly used device is the Lithium-ion battery. But even though it has high energy density, its power density is relatively low (figure 7). Besides, its number of charging/discharging cycles is small and the battery's characteristics will degrade quickly over time. It is then unlikely to use only batteries to store braking energy. An intermediate storage device is needed to adapt the instantaneous braking power peaks (figure 1) to the batteries limited power. It is clear from the figure 7 that supercapacitors (also known as Ultracapacitors) are the most suitable for this application. In fact, a supercapacitor uses a different storage mechanism than batteries. The energy is stored electrostatically instead of electrochemically, what gives it a high power density. In addition, supercapacitors can last for millions of charge/discharge cycles without losing energy storage capability.

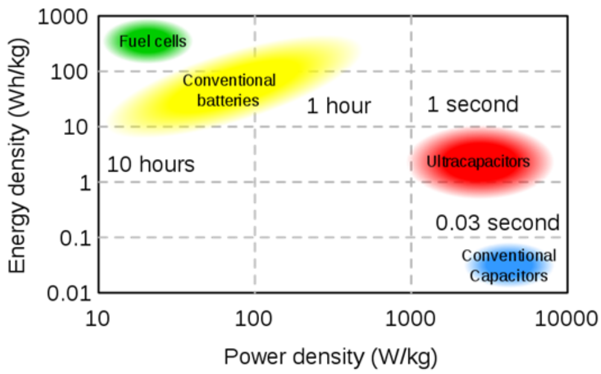

Figure 7 : Energy Density & Power Density of Energy Storage Technologies – Image from Wiki Commons

Therefore, a hybrid storage system is used to store the braking energy. It consists of two cascaded stages: the first one is a buck-boost converter controlled to charge the supercapacitor with the recuperated braking power and to discharge it when a hybrid bus arrives to the station. The second is also a buck-boost converter controlled to charge/discharge the battery with a constant current. The figure below shows the hybrid storage system modelled using Simulink:

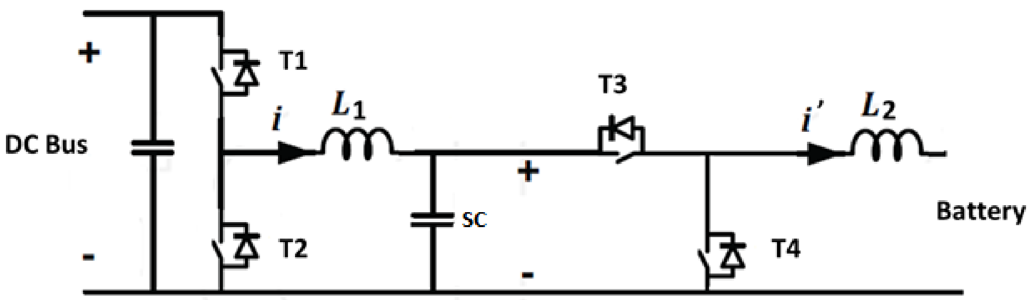

Figure 8 : Hybrid storage system model

This model is controlled with two control loops, one for each converter. The command signal of T1/T2 ensures that the power absorbed/delivered by the supercapacitor is equal to the reference power (Pref). Pref depends of the Supercapacitor state of charge (SOC). It is calculated based on table 2. The figure below shows the corresponding control loop:

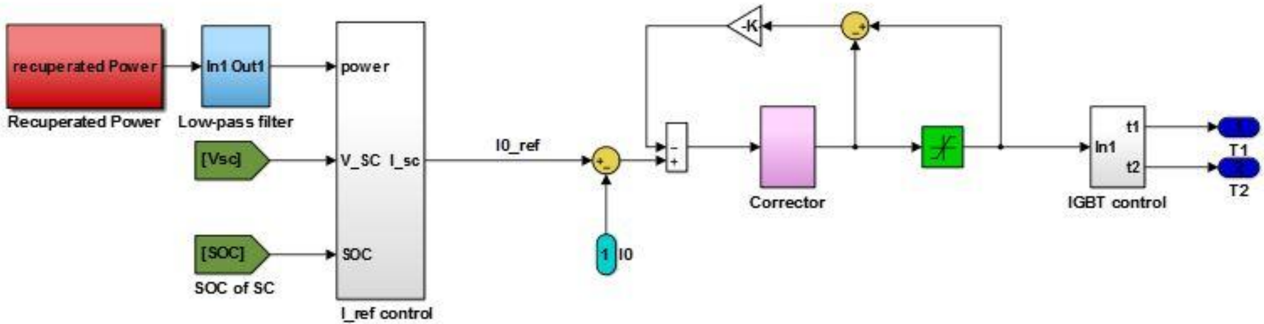

Figure 9 : Supercapacitor control loop

The figure below shows the reference current and the measured current of the supercapacitor.

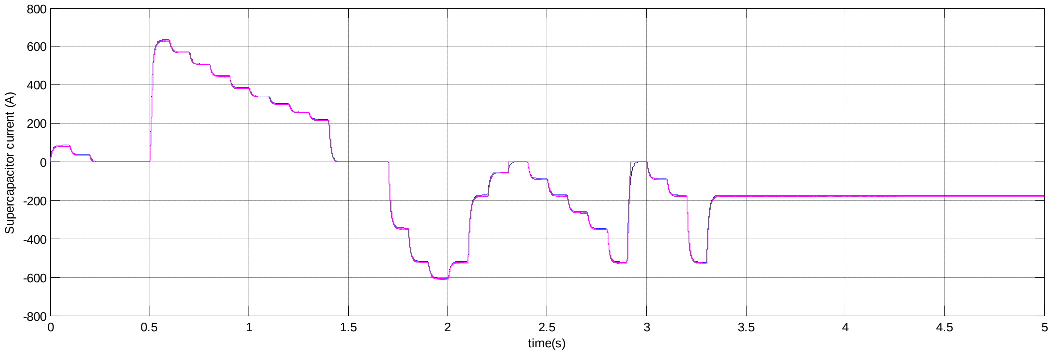

Figure 10 : reference current I0_ref (Blue) and the measured current I0 (Pink) of the supercapacitor

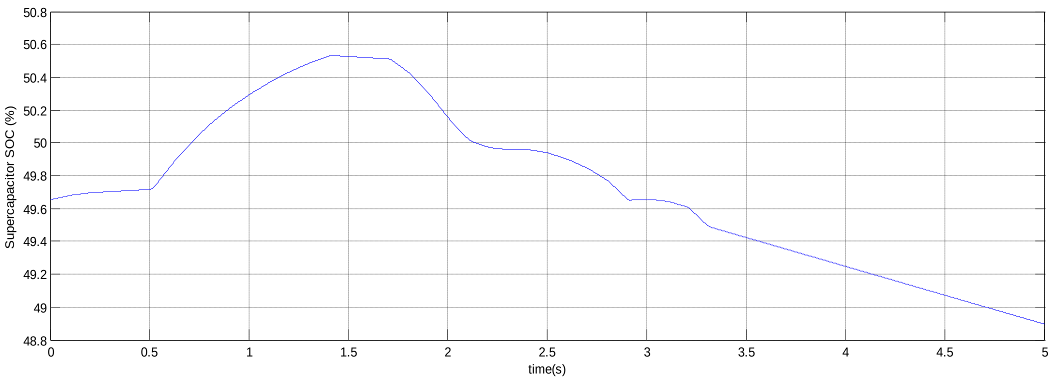

Figure 11 : Supercapacitor SOC per unit

The control loop below ensures that the battery is charged and discharged with a constant nominal current (Ibat = In). The charging/discharging modes are shown in table 2. The battery's reference current (I_bat_ref) depends on the SOC of the supercapacitor. Both modes attempt to bring back the SOC to 50%. Effectively, the system should be able to respond quickly to the operation mode selected by the EMS and which will be speeded-up with a SOC equal to 50%. The figure below shows the corresponding control loop:

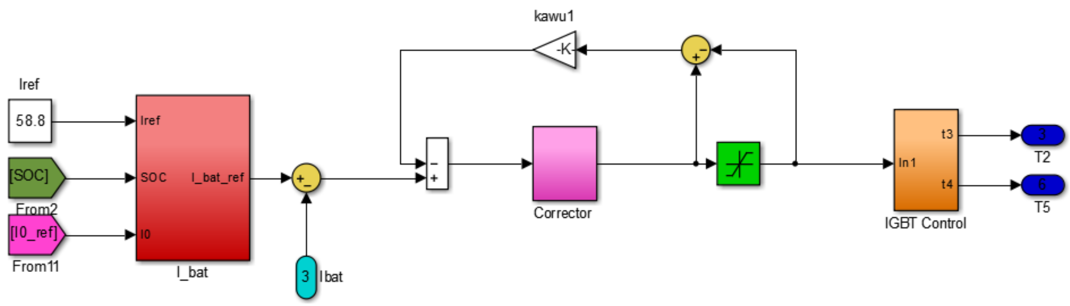

Figure 12 : Battery's control loop

The table 2 represents how the EMS controls the hybrid storage system:

Charging mode		
Supercapacitor SOC	**Supercapacitor Pref**	**Battery reference current**
SOC < 50%	Pref=Prec*	Ibat** = 0
50% < SOC < 95%	Pref=Prec*	Ibat** = In
95% < SOC <100%	Pref = (-20*SOC+20).Prec*	Ibat** = In
Discharging mode		
Supercapacitor SOC	**Supercapacitor Pref**	**Battery reference current**

SOC < 25%	Pref = 0	Ibat = - In
25% < SOC < 30%	Pref = (20*SOC-5)	Ibat = - In
30% < SOC < 50%	Pref=P_discharge	Ibat = - In
50% < SOC < 100%	Pref=P_discharge	Ibat = 0

* Recuperated braking power absorbed by the SC ** Battery's reference current

Table 2 : Hybrid storage energy management

2.3 System Simulation

In order to demonstrate the efficiency of the DC grid concept, separate simulations should be done using ELBAS, Alstom Transport's multi-train simulator, and Matlab-Simulink because it is not possible to create a direct link between ELBAS and Simulink allowing a simultaneous simulation. Therefore, the railway system is first simulated using ELBAS. The output of this simulation is the recuperated power as function of time. It is given in an Excel file format and then saved in Matlab variables to be used in the Simulink model. The figure below shows the simulation steps:

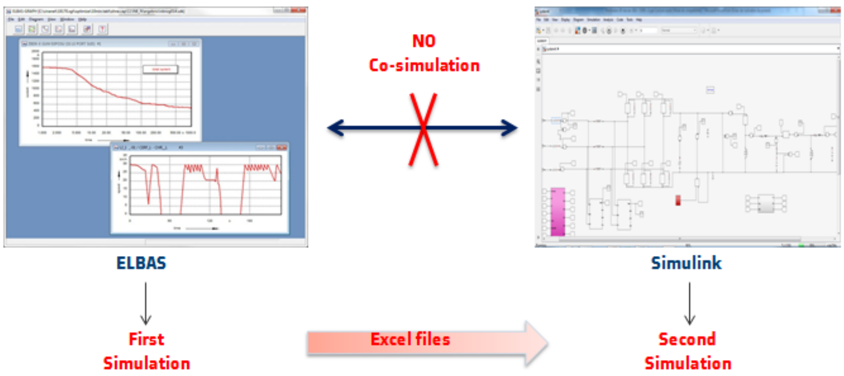

Figure 13 : Simulation steps

2.3.1 ELBAS simulation

In this study, the simulation is based on RATP metro line 13 in Paris to evaluate the amount of braking energy that can be stored.

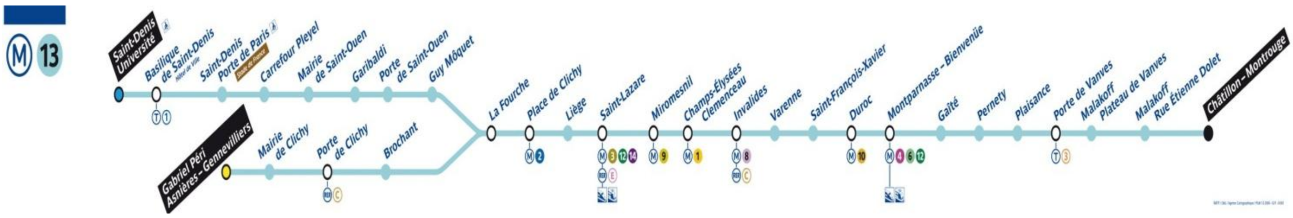

Figure 14 : Paris Metro line 13

It is considered that the hybrid buses charging station will be located at "Porte de Saint-Ouen". Therefore, the line was simulated from "Invalides" station in the direction to "Saint-Denis Université" and "Gabriel Péri Asnières-Gennevilliers". In fact, the energy consumption at "Porte de Saint-Ouen station" is independent from the other part of the line, then it is sufficient to simulate from " Invalides" station.

Four Scenarios have been simulated, each one corresponding to a different headway:

Interval	Headway (seconds)
5h30-7h30	175
7h30-10h30	95
10h30-16h30	175
16h30-19h30	100
19h30-21h30	175
21h30- 1h00	290

Table 3 : Metro line 13 Schedule

The simulation time was calculated in a way to take into consideration different possible trains crossings:

Headway (s)	Simulation time
95	2 h 23 min
100	2 h 38 min
175	5 h 08 min
290	5 h 50 min

Table 4 : Simulation time calculated for each headway

In order to recuperate the braking energy, a converter was placed at “Porte de Saint-Ouen” station. When the trains brake, the line voltage increases. To protect the line from over-voltages, the on-board rheostats are activated when the voltage reaches 900V. Therefore, the input voltage of the converter should be less than 900V and higher than the no load voltage of the nearest substation to avoid consuming energy from this substation. In this case, it is “Saint Ouen” substation with a 750V no-load voltage. The converter’s input voltage was then set to a value of 820V.

The simulations were done with a 1 second time step and a 10 meters KP (Kilometric point) step. ELBAS calculated the converter’s recuperated power at each time step. The figure below shows the converter’s time function power curve. It is extracted in an Excel file to be used as an input to Matlab-Simulink model.

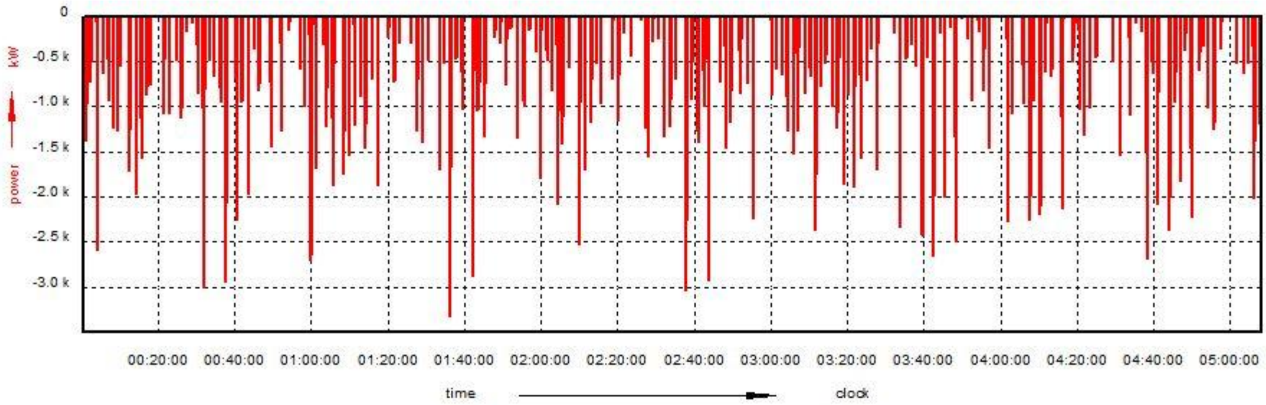

Figure 15 : Converter’s time function power curve extracted from ELBAS

2.3.2 Matlab-Simulink simulation

After extracting the recuperated power from ELBAS, the system was simulated in Matlab-Simulink to evaluate the amount of energy that can be stored. The figure below represents the braking energy distribution during 1 hour :

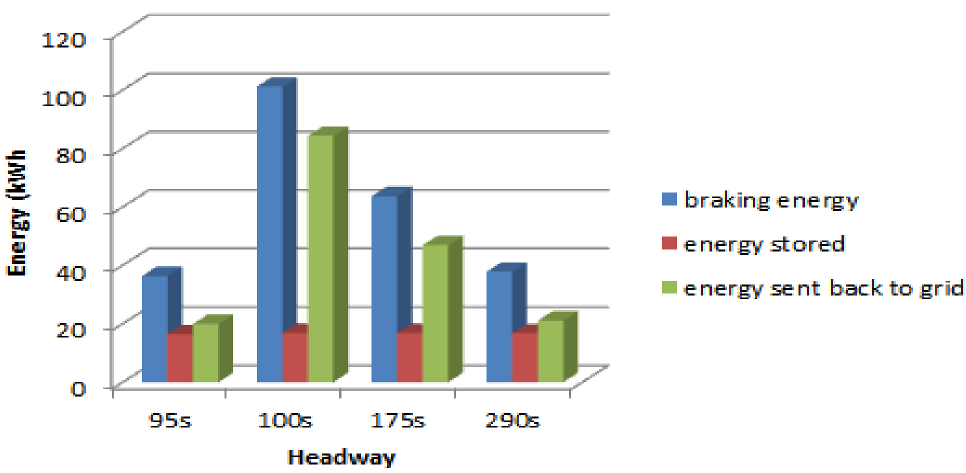

Figure 16 : Braking energy distribution during 1 hour

Even if the braking energy varies from headway to another, the energy stored is approximately stable. It varies between 16.33 kWh and 16.82 kWh. This energy will be enough to charge every 1 hour a hybrid bus with a constant power of

200 kW during 4 minutes. On the other hand, the energy sent back to the grid will be used by the loads in the station (light, screens, escalators...) which will reduce the total energy bill.

3. Conclusion

This paper presented a smart DC micro-grid solution for reducing braking energy losses in railway systems. It studied the possibility to store this energy and re-use it in other applications. It consisted of a DC busbar connecting different components: the inverter used to regulate the DC busbar voltage, the DC/DC converters used to connect the railway system, the static loads, the hybrid buses and finally the hybrid storage system. All these components were controlled by an EMS that is important to optimize power flow and energy consumption in a plug-and-play manner. Simulations have shown that it is possible to recuperate a sufficient amount of energy to charge hybrid buses every 1 hour. The advantage of this solution is that it is connected to the low voltage grid (230V/400V) and no additional contract is needed to charge the buses, in contrary, the excess of braking energy will be used internally by other loads in the station which will reduce the total energy consumption.

It is important to mention that these results depend of the simulated railway system. They could change considerably from one line to another. Therefore, each line should be considered as an independent use case that should have its own dedicated study.

4. Acknowledgements

This study would not have been possible without the guidance and the help of several individuals who in one way or another contributed in it. First, I would like to thank Alstom Transport for giving me the opportunity to work on the European project OSIRIS and helping me developing my skills.   In addition, a thank you for Supélec for giving me the academic support I needed. I would like to thank also Ratp for their contribution in this work. Finally, I am grateful for the ANRT (association nationale de recherche et de technologie) for believing in this innovative project and financing my thesis.

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